

BIOMECHANICAL GAIT CHARACTERISTICS OF UNSUCCESSFUL FOOT CLEARANCE  
DURING SWING IN INDIVIDUALS WITH CHRONIC STROKE

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## Abstract

**Background and Objective:** Individuals with hemiparesis secondary to chronic stroke commonly display motor impairments that result in altered biomechanical characteristics of gait. These abnormalities increase the risk of falls and injury during ambulation. Lower extremity gait impairments have been previously described compared to the non-paretic limb or healthy control subjects. Unfortunately, the biomechanical parameters underlying instances of unsuccessful foot clearance (i.e., trips) during the swing phase of gait have yet to be examined. The purpose of this study was to examine the paretic lower extremity spatiotemporal, kinematic, and kinetic characteristics of trips during the gait cycle in individuals with chronic stroke.

**Methods:** Gait data for 26 subjects with chronic stroke were obtained during a 20 minute gait training session on a dual-belt ‘instrumented’ treadmill. Force plate data were examined to identify naturally occurring trips during the swing phase of the paretic limb. Instances of successful foot swing immediately prior to each trip were also identified. Spatiotemporal (double support time), kinematic (hip, knee, and ankle angles), and kinetic (propulsive impulse and hip, knee, and ankle moments) measures of the paretic limb occurring during late stance, toe-off, and swing were collected for each trip and step with successful foot clearance. These data were compared across subjects and Pearson correlation coefficients were used to determine relationships between variables.

**Results:** In the paretic limb, the ankle angle at toe off ( $p = 0.003$ ), knee flexion velocity at toe off ( $p < 0.001$ ), and peak knee extension moment during terminal stance ( $p < 0.001$ ) were significantly different between trips and steps with successful foot clearance. Knee flexion velocity moment correlated significantly ( $p < .05$ ) with the other significant parameters. The mean differences in significant parameters during trips were  $1.1^\circ$  more ankle plantarflexion at toe off, knee flexion velocity reduced by  $17.6^\circ/\text{sec}$ , and peak knee extension moment increased by  $0.01\text{Nm/kg}\cdot\text{m}$  during terminal stance.

**Conclusions:** The qualitative differences in the parameters between instances of successful and unsuccessful foot clearance are relatively small in individuals with hemiparesis secondary to chronic stroke. Only minor changes in the movement of the paretic limb can result in a trip. Additionally, the multi-joint biomechanical changes occurring in the paretic limb during unsuccessful foot clearance result in a functionally longer limb. Thus, interventions targeting multiple joints in the paretic limb may be needed to reduce the risk of trips in these individuals.

## Introduction

Each year, nearly 800,000 people in the US experience a stroke.<sup>1</sup> The multiple consequences of stroke are a leading cause of impairment, disability, and death. Hemiparesis is a common motor deficit occurring post-stroke that negatively impacts function and often persists into the chronic stages of recovery following stroke.<sup>2</sup> Individuals with chronic hemiparesis secondary to stroke often exhibit disturbances in lower limb movement patterns that can be attributed to the muscle weakness, abnormal motor control, and impaired coordination.<sup>3,4</sup> These impairments may adversely affect balance, transfers, and walking ability leading to falls and further deficits in functional abilities.

Falls and fall-related injuries are common complications following stroke.<sup>5</sup> The detrimental consequences of falls include fractures, soft tissue injury, hospitalizations, decreased mobility, and negative psychological impacts such as fear and anxiety.<sup>6</sup> Additionally, falls after stroke are associated with poor rehabilitation outcomes, loss of independence, and chronic disability.<sup>7</sup> Falls most often occur during mobility tasks such as walking and transfers in individuals with chronic stroke.<sup>8</sup> Common gait deviations that occur following stroke such as decreased walking speed, reduced foot clearance, and stance time asymmetries are purported to contribute to the risk for falling.<sup>6</sup> Due to the increased risk for falls during ambulatory activities, improvement of walking ability is a primary goal in stroke rehabilitation.

Quantifying hemiparetic gait dysfunction is a critical step towards designing effective intervention strategies for gait rehabilitation. Hemiparetic gait impairments following stroke can vary considerably amongst patients, and are largely influenced by the severity of the lower limb neuromuscular deficits.<sup>9</sup> Several previous investigations have identified and classified common patterns of hemiparetic gait abnormalities.<sup>10,11</sup> Decreased walking speed, reduced step length,

reduced stance time on the paretic limb, and increased time spent in double support are common characteristics of hemiplegic gait.<sup>12</sup> The causes of these spatiotemporal abnormalities have been linked to alterations in lower limb mechanics.<sup>13</sup> Specifically, paretic joint kinematic patterns often include reductions in hip flexion, knee flexion, and ankle dorsiflexion during swing, as well as decreased hip extension, knee flexion, and ankle plantar flexion at toe-off.<sup>11</sup> Lower limb kinetic alterations such as reductions in hip, knee, and ankle joint moments and powers during late stance and pre-swing have also been identified.<sup>14,15</sup>

The overall result of these paretic limb biomechanical alterations is the presence of a functionally longer limb during swing which challenges successful foot clearance. Compensatory movements at the trunk and pelvis such as hip hiking and leg circumduction may be utilized to overcome these abnormalities in distal joint motion.<sup>16</sup> Altered late stance joint mechanics and/or compensatory motions during swing may negatively impact paretic limb advancement. Unsuccessful foot clearance (i.e., a trip) during the swing phase of gait can cause falls and further injury to individuals following stroke. Previous studies have focused on examining the biomechanical patterns that characterize hemiparetic gait<sup>10,11</sup> as well as the pathophysiology surrounding falls in post-stroke populations.<sup>5,6</sup> However, the biomechanical parameters underlying instances of unsuccessful foot clearance have yet to be examined. Our aim is to examine the parameters leading to naturally occurring trips during ambulation. This experimental design is notably different than previous studies that induced trips in subjects via perturbations or unexpected obstacles.<sup>17,18</sup>

The purpose of this study is to determine the spatiotemporal, kinematic, and kinetic characteristics of the paretic limb associated with unsuccessful foot clearance in subjects with chronic hemiparesis secondary to stroke. We hypothesized that subjects will exhibit

biomechanical alterations during late stance, which will lead to a functionally longer paretic limb in swing phase. The paretic leg posture we expected to see during trips, compared to instances of successful foot clearance, included decreased pelvic obliquity throughout the swing phase, decreased hip flexion at toe-off and during swing phase, decreased knee flexion during swing, and increased ankle plantarflexion during swing. By exploring potential patterns demonstrated during trips, we can design targeted interventions to improve walking ability and decrease falls post-stroke.

## **Methods**

### *Subjects*

Forty subjects with chronic (>6 months) hemiparesis secondary to stroke were recruited as part of a larger study examining gait kinematics and kinetics during treadmill ambulation. Twenty six subjects who demonstrated unsuccessful foot clearance during training on the treadmill were analyzed for this study. Additional inclusion criteria were (1) clinical symptoms consistent with an ischemic or hemorrhagic unilateral cortical brain lesion, resulting in sensory motor dysfunction more than 6 months prior to recruitment, and (2) the ability to walk a minimum of 10 m overground without physical assistance. Stroke was determined via subject self-report and confirmed by a physician while receiving medical clearance for study participation. Participants were excluded from training if they exhibited additional neurologic (e.g., Parkinson's disease, vestibular disorders), musculoskeletal, or cardiovascular pathology that would preclude gait training, or had a history of balance deficits or falls unrelated to the stroke. Subjects who wore an ankle foot orthosis (AFO) during training were also excluded due to the imposed alterations in lower limb joint mechanics from the AFO. All subjects signed an informed consent form which was approved by the IRB at UNC Chapel Hill.

### *Data collection*

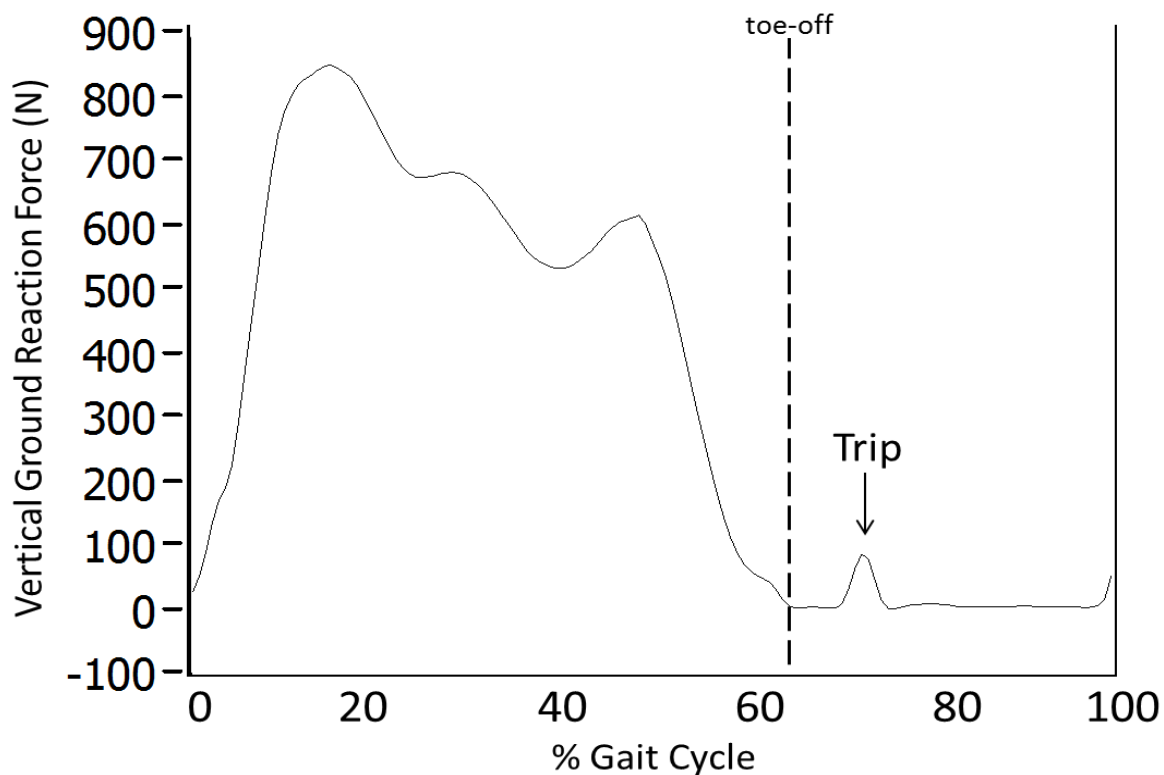
Gait data for each subject were obtained from a 20 minute gait training session on a dual-belt ‘instrumented’ treadmill (Bertec Corp., Columbus, OH). Treadmill speed for each subject was chosen by the principal investigator as a speed that the subject could maintain for the duration of the training session, with the goal of a heart rate of 70% of max or RPE of 14 on the Borg scale. All participants wore an overhead safety harness while walking, which did not restrict lower limb movement. Subjects did not use assistive devices during training and no manual facilitation was provided to alter subjects’ gait patterns. A handrail was available for subjects to hold onto, although they were discouraged from doing so.

While walking on the treadmill, limb movement data was collected in 3-dimensional space. Lower extremity motion was recorded using an 8-camera motion capture system (Vicon Corp.) at 120 Hz, as ground reaction forces (GRFs) were sampled concurrently at 960Hz from both sides of the Bertec treadmill. Limb segments were tracked with retroreflective markers taped to the subject’s pelvis, legs, and feet. Details describing marker placement setup have been previously described.<sup>19</sup> Following data collection, Visual3D software (C-Motion, Germantown, MD) was used to identify the locations of the markers and model the three-dimensional motion of the pelvis and lower limb segments. Marker trajectories and GRF data were low-pass filtered at 6Hz and 20Hz, respectively. Hip, knee, and ankle joint angles were computed using Euler angles and internal joint moments were computed using an inverse dynamics approach. Joint powers were computed as the product of the joint moment and the angular velocity.

### *Data Management*

All instances of unsuccessful foot clearance (trips) during the 20 minute gait training session were initially identified. These trips were identified by the presence of a vertical GRF

which exceeded 10N on the paretic limb's treadmill belt during its respective swing phase (see Figure 1). Instances of successful foot swing during the stride immediately prior to each trip were also identified and labeled. For subjects demonstrating a large number of trips during the training session a maximum of 18 steps were used for analysis.



**Figure 1.**

Paretic limb vertical ground reaction force (GRF) from a representative subject. The dashed line demarcates the point of toe-off and initiation of swing phase in the gait cycle. A vertical GRF > 10 N detected during the swing phase represents a trip.

Because we were interested in the biomechanics influencing the swing phase dynamics of the paretic limb, we focused our data collection on the late-stance, toe-off, and swing phases of the gait cycle. The spatiotemporal measure of interest was double support time (non-paretic heel strike to paretic toe-off in seconds). Pre-swing kinematic measures were peak hip extension angle at late-stance, knee flexion velocity at toe-off, and ankle angle at toe-off. Swing-phase kinematic measures included peak hip, knee, and ankle flexion angles and circumduction (frontal

plane excursion of the swing foot with respect to the stance foot). Kinetic measures collected were propulsive impulse and the peak hip flexion, knee extension, and ankle plantarflexion moments during late-stance. Spatiotemporal, kinetic, and kinematic variables were calculated for each labeled step using custom written LabVIEW software (National Instruments, Austin, TX). Outcome measures of successful and unsuccessful foot clearance were then averaged for each subject.

### *Statistical analysis*

Within-subject statistical analyses were performed for each outcome variable using SPSS, ver 16 (SPSS, Chicago, IL). Paired-samples t-tests were used to compare outcome measures between instances of successful and unsuccessful foot clearance. Adjustments for multiple comparisons was performed by reducing the alpha level (.05) by the number of comparisons made (e.g., 12 variables/0.05 = 0.004). A significance level of  $\alpha=0.004$  was used for all between condition comparisons. Pearson correlations were then calculated to determine the presence of relationships between the variables determined to be significantly different between trip and non-trip steps. An  $\alpha=0.05$  was used to assess the correlations.

## **Results**

Twenty-six subjects demonstrated naturally occurring trips during the gait training sessions and were included in the gait analysis. Demographic data of the subjects are described in table 1. Overground gait speed was 0.73 m/s ( $\pm 0.33$ ; range 0.22-1.28), and treadmill gait training speed was 0.68 m/s ( $\pm 0.27$ ; range 0.20-1.3). An average of 10.0 ( $\pm 5.7$ ) trips and corresponding steps with successful foot clearance were analyzed for each of the 26 subjects.



**Table 1.**  
Demographic Characteristics of Subjects Who Demonstrated Trips During Gait Training (N=26)

	Mean	SD	Range
Age (y)	56.0	11.5	(35-81)
Time post stroke (months)	59.5	75.9	(9-333)
Gait speed (m/s)	0.68	0.27	(0.2-1.3)
Fugl-Meyer Motor Function LE	23.9	4.40	(14-31)
Berg Balance Scale	48.8	5.5	(38-56)
Number of subjects			
Paretic side (Right/Left)	15/11		
AFO	2		
Assistive device	2		

The means and standard deviations of the 12 variables measured during trips and steps with successful foot clearance are presented in table 2. Two of the 8 spatiotemporal and kinematic variables were significantly altered between trips and steps with successful foot clearance. Ankle angle at toe-off had a mean difference of 1.1 degrees more plantarflexion during trips ( $p = 0.003$ , Fig. 2). Knee flexion velocity at toe-off had a mean reduction of 17.6 degrees/second during trips ( $p < 0.001$ , Fig. 3). The spatiotemporal measure of double support time was not significantly altered between trips and steps with successful foot clearance ( $p = 0.41$ ). Similarly, 5 of the 7 kinematic variables were not found to be significantly different during trips. These include peak hip extension at late stance ( $p=0.87$ ), circumduction during swing ( $p=0.52$ ), and swing phase peak hip flexion, knee flexion, and ankle dorsiflexion ( $p=0.23$ ,  $p=0.19$ ,  $p=0.77$ , respectively).

One kinetic measure was significantly different between trips and steps with successful foot clearance. Peak knee extension moment at late stance had a mean increase of 0.01 Nm/kg·m

during trips ( $p < 0.001$ , Fig. 4). Propulsive impulse ( $p=0.57$ ) as well as peak hip flexion ( $p=0.50$ ) and ankle plantarflexion ( $p=0.57$ ) moments during late stance were not significantly altered.

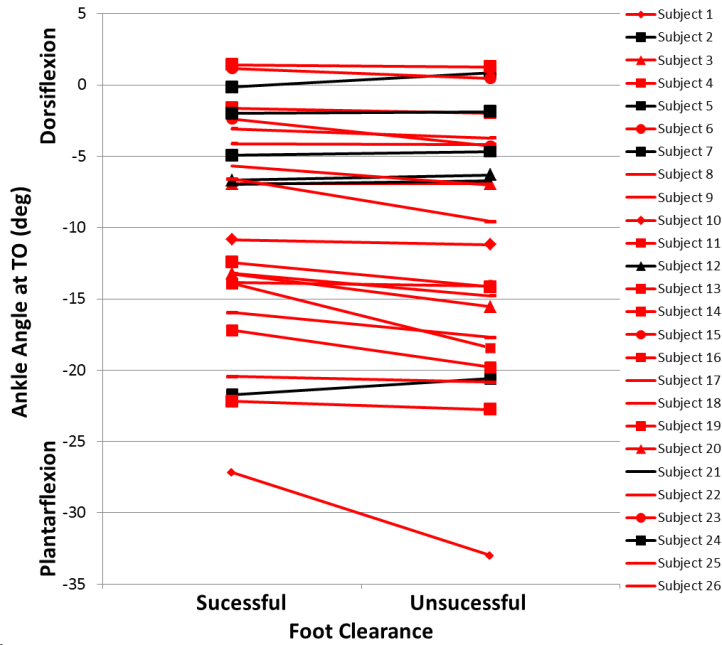
**Table 2.**

Spatiotemporal, Kinematic, and Kinetic Measures of the Paretic Limb During Trips and Steps with Successful Foot Clearance

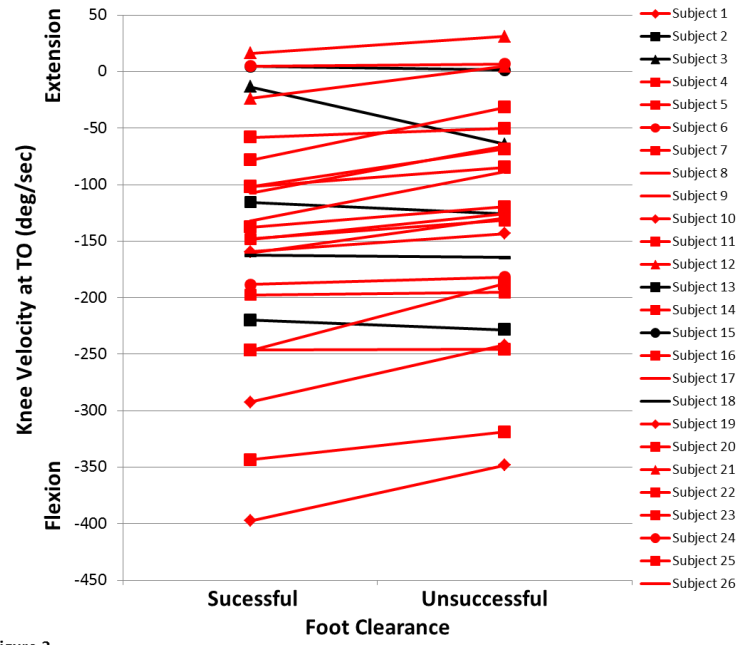
	Trips		Successful Foot Clearance		P-Value
	Mean	(SD)	Mean	(SD)	
<b>Spatiotemporal</b>					
Double support time (sec)	0.29	(0.10)	0.28	(0.10)	0.41
<b>Kinematic</b>					
Peak hip extension angle late stance (deg)	10.47	(7.32)	10.41	(7.50)	0.87
Knee flexion velocity toe-off (deg/sec)	126.90	(98.45)	144.48	(105.33)	<0.001*
Ankle plantarflexion angle toe-off (deg)	10.68	(8.69)	9.54	(7.85)	0.003*
Peak hip flexion angle swing (deg)	29.80	(8.16)	29.69	(8.45)	0.79
Peak knee flexion angle swing (deg)	42.61	(12.05)	42.05	(12.80)	0.19
Peak dorsiflexion angle swing (deg)	-3.97	(5.89)	-3.90	(6.04)	0.77
Circumduction swing (mm)	0.05	(0.04)	0.06	(0.04)	0.52
<b>Kinetic</b>					
Propulsive impulse	12.88	(7.92)	12.68	(7.87)	0.57
Peak hip flexion moment late stance (Nm/kg·m)	0.30	(0.10)	0.29	(0.11)	0.50
Peak knee extension moment late stance (Nm/kg·m)	0.12	(0.05)	0.11	(0.05)	<0.001*
Peak plantarflexion moment late stance (Nm/kg·m)	0.54	(0.12)	0.55	(0.13)	0.57

\*Statistically significant different between Trips and Successful Foot Clearance.

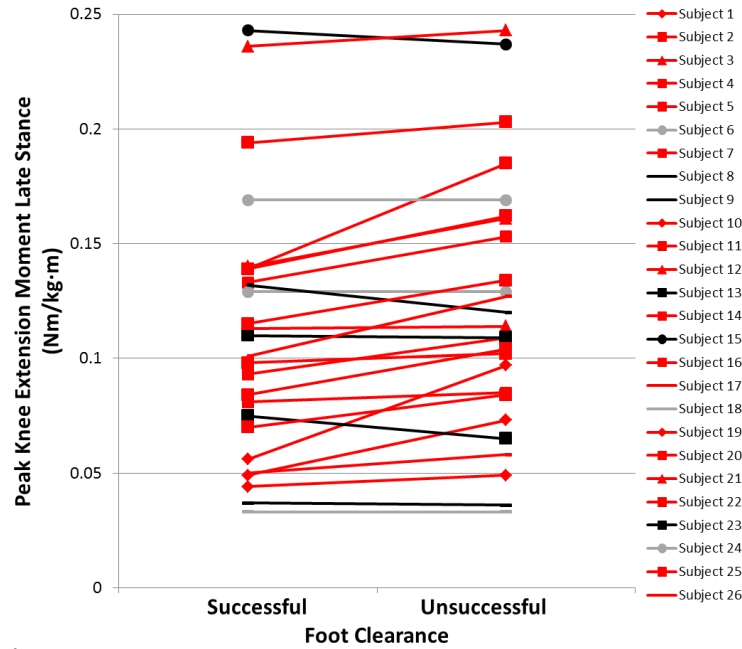
A Pearson Correlation of the three variables that were found to be significantly different between trips and steps with successful foot clearance revealed a significant relationship between knee flexion velocity at toe-off and ankle angle at toe-off ( $r = 0.45$ ,  $p < 0.05$ ) as well as knee flexion velocity at toe-off and peak knee extension moment during late stance ( $r = -0.54$ ,  $p < 0.01$ ). Specifically, the reduction in knee flexion velocity at toe-off that was observed during trips is associated with increased ankle plantarflexion angle at toe-off. Decreased knee flexion velocity toe-off was also correlated with an increased knee extension moment during late stance.



**Figure 2.** Mean changes in ankle angle at toe-off between steps with successful foot clearance and trips in 26 subjects. Red lines represent subjects who demonstrated an increase in ankle plantarflexion during trips (N=20). Black lines represent subjects who demonstrated a reduction in ankle plantarflexion during trips (N=6).



**Figure 3.** Mean changes in knee flexion velocity at toe-off between steps with successful foot clearance and trips in 26 subjects. Red lines represent subjects who demonstrated a decrease in knee flexion velocity during trips (N=21). Black lines represent subjects who demonstrated an increase in knee flexion velocity during trips. (N=5).



**Figure 4.** Mean changes in peak knee extension moment during late stance between steps with successful foot clearance and trips in 26 subjects. Red lines represent subjects who demonstrated increased knee extension moments during trips (N=18). Black lines represent subjects who demonstrated decrease knee extension moments during trips (N=5). Grey lines represent subjects who demonstrated no change in knee extension moment (N=3).

## Discussion

The hypothesis that lower extremity kinematics and kinetics would be different during instances of unsuccessful foot clearance was partially supported by the data. Comparisons between steps with and without successful foot clearance revealed that peak knee extension moment, knee flexion velocity, and ankle angle were significantly altered during trips. Specifically, trips were characterized by an increase in the knee extension moment during late stance and ankle plantarflexion angle at toe-off as well as a reduction in the knee flexion velocity at toe-off. These kinematic and kinetic changes that occurred at the knee and ankle joints were related to each other, and may have produced a functionally longer paretic limb during swing phase which contributed to unsuccessful foot clearance. Contrary to our hypothesis, there were no significant changes in biomechanical parameters at the hip or pelvis associated with steps that resulted in a trip.

An overall lengthening of the paretic limb during swing has been demonstrated in many kinematic and kinetic analyses of hemiparetic gait.<sup>10,11,13</sup> Diminished flexion at the hip, knee, and ankle are common post-stroke gait deviations occurring during pre-swing and swing phases. These abnormalities have been attributed to a multitude of stroke-related impairments including decreased strength, increased muscle tone, and irregularities in muscle activation timing.<sup>13,20</sup> Paretic limb motor insufficiencies negatively impact the multi-joint flexion and effective limb shortening that is needed in order to achieve foot clearance during swing phase. The kinematic and kinetic changes that contribute to a longer paretic limb and the associated compensatory movements have frequently been described in comparisons to the non-paretic limb or healthy control subjects.<sup>10,11,21</sup> However, the direct association between factors that would lengthen the paretic limb and a resulting trip has not been previously reported in individuals post-stroke. Our

data suggest that diminished flexion at the knee and ankle joints contribute to the inability to successfully shorten the limb and achieve sufficient foot clearance during swing.

We noted that the kinematic and kinetic differences between instances of successful and unsuccessful paretic limb foot clearance are quantitatively small. This suggests that a trip can result from only minor changes in the movement of the paretic limb at each joint. Nevertheless, the biomechanical changes we identified leading to trips are similar in magnitude to the minimal detectable change (MDC) values reported for gait parameters during treadmill walking in individuals with post-stroke impairments.<sup>22</sup> Although the alterations are small, their similarity in size to these MDC values provides evidence that our findings represent real changes contributing to trips.

Additionally, the magnitude of the changes we observed suggests that individuals with hemiparesis are at a high risk of tripping with every step. In unimpaired subjects, the minimum vertical distance between the toe and the walking surface (i.e., minimum foot clearance) occurs approximately half-way through swing phase.<sup>23</sup> It is suggested that this variable is directly associated with the potential for trips during ambulation since it represents a critical time during swing when the toe is at its closest distance to the ground, approximately 1.5 cm.<sup>23,24</sup> Multiple gait parameters such as segmental angular velocities, joint range of motion, and the coordination of joint moments influence minimum toe clearance and successful forward limb progression during swing.<sup>25</sup> However, the trajectory of the swing limb and the conditions needed to achieve minimum toe clearance are largely determined by kinematic and kinetic events occurring prior to the initiation of swing.<sup>26,27</sup> This is consistent with our finding that kinematic and kinetic alterations occurring during late stance and toe-off lead to the inability to successfully clear the foot during swing and resultant trips.

Minimum toe clearance has not yet been examined in hemiparetic gait. However, an increase in minimum toe clearance variability between strides has been identified in elderly subjects and may contribute to an increased risk for trip-related falls due to the small margin for error that this distance allows.<sup>28,29</sup> While the underlying mechanisms of age-related increases in toe clearance variability are not clear, they may be attributable to neuromuscular impairments, such as reduced proprioceptive ability and altered motor control<sup>29</sup>, that are also common in individuals with chronic stroke.<sup>30</sup> Our study did not aim to quantify minimum toe clearance or variability in toe clearance; however, we know that the minimum toe clearance was equal to zero for each trip. If stroke-related impairments lead to an increase in toe clearance variability, this may help explain why very small kinematic and kinetic alterations can lead to a trip.

An important finding in this investigation is that trips occurred due to biomechanical changes at multiple joints in the paretic limb. This finding is in contrast with the idea that unsuccessful foot clearance during paretic swing phase may be primarily due to single-joint abnormalities, specifically ankle joint insufficiencies resulting in foot-drop or reduced dorsiflexion.<sup>31-33</sup> Ankle-foot orthoses (AFOs) are commonly prescribed for individuals with hemiparesis secondary to stroke to assist with foot clearance and increase stability during ambulatory activities.<sup>34</sup> Improvements in gait speed, efficiency, and pattern have been demonstrated with the use of AFOs.<sup>35</sup> However, AFOs may only have negligible effects on improving overall lower limb kinematics and kinetics to assist with successful foot clearance in hemiparetic individuals.<sup>36,37</sup> Our finding that trips result from alterations occurring at multiple joints suggests that use of an intervention targeting single-joint gait abnormalities, such as an AFO, by itself may not prevent all trips. All subjects included in this study were able to walk on a treadmill without use of an AFO. Therefore, the influence of AFOs on trips cannot be

delineated from our investigation. However, given that the biomechanical changes which lead to trips occurred at multiple joints, it is reasonable to suggest that interventions designed to address multi-joint impairments may be more effective for reducing the risk for trips and resultant falls during ambulation.

Biomechanical alterations at the ankle resulting in trips were observed in our study; however, knee flexion and extension mechanics also significantly contributed to trips. Reduced knee flexion velocity at toe-off and an increased knee extension moment during late stance are causes of a stiff-knee gait pattern often demonstrated by individuals with neurological deficits such as stroke and cerebral palsy.<sup>16</sup> Previous studies have found that a stiff-knee gait pattern can inhibit foot clearance and result in trips during walking.<sup>38</sup> Stiff-knee gait in individuals with CP and stroke is attributed to overactivity of the rectus femoris muscle during swing.<sup>39,40</sup> Exaggerated activation of the quadriceps during late stance and early swing has been shown to be elicited by hyperexcitable heteronymous reflex activity from hip flexor muscles following stroke.<sup>41,42</sup> That is, inappropriate knee extensor activity in stiff-knee gait during swing may be the result of a reflexive response to hip extension during late stance.<sup>42</sup> In contrast to those findings, our study did not detect any alterations in hip kinematics associated with the observed reduction in knee flexion velocity and increased knee extension moments that lead to trips, although we did not assess hip extension velocity. Stiff-knee gait is often treated via surgical transfer of the rectus femoris insertion to a site that reduces its contribution to the internal knee extension moment. Post-operative improvements in walking ability in the CP population have been associated with increased knee flexion velocity and reduced knee extension moments prior to toe-off.<sup>26</sup> Treatment of stiff-knee gait via botulinum toxin injection in the rectus femoris of

hemiparetic subjects has also been shown to effectively normalize knee angular position and velocity during late stance and swing.<sup>43</sup>

We cannot directly attribute the changes in knee biomechanics we observed during trips to altered muscle activity due to a lack of EMG data. However, the studies on individuals with stiff-knee gait suggest that interventions targeting the muscles which influence knee angular motion during swing can reduce some of the variables that lead to trips in individuals post-stroke. Altering the swing phase dynamics alone may not be sufficient for reducing trips, however. Increasing knee flexion torque during swing, for example, has not been shown to normalize gait patterns following stroke. In fact, an orthotic which applied knee flexion torque to the paretic limb during swing actually increased hip abduction, a compensatory movement used to facilitate foot clearance.<sup>44</sup> This supports our findings that successful foot clearance is not dependent upon knee swing phase biomechanics, but instead is influenced primarily by kinematic and kinetic conditions at late stance and toe-off.

Ankle plantarflexion at the end of stance can also critically influence swing phase dynamics.<sup>23</sup> We found that plantarflexion of the paretic ankle at toe-off is greater during trip steps. During normal gait, the ankle plantarflexes at the end of stance to provide a forward propulsive force, but then dorsiflexes during swing to allow toe clearance as the limb advances forward.<sup>23,45</sup> Excessive plantarflexion during late-stance and toe-off may result in insufficient dorsiflexion at the time of critical toe clearance during swing.<sup>46</sup> In individuals with chronic stroke, excessive plantarflexion prior to toe-off may be due to contractures or spasticity in the plantarflexor muscles or may be related to movements occurring further up the limb.<sup>25</sup>



### *Limitations*

All subjects included in this study were able to independently ambulate for a total of twenty minutes on a treadmill. In order to achieve twenty minutes of treadmill training with minimal rest breaks, the treadmill speed was determined prior to testing and may not have been representative of the subject's self-selected or over-ground walking speed. Lower extremity kinematics and kinetics are altered with walking speed<sup>47</sup>; however, comparisons were made between trip and non-trip steps, so gait speed was not a factor in those differences.

Additionally, the subjects' fall histories were not obtained during this study. Previous investigations have noted variations in gait characteristics between elderly subjects with a history of falls and elderly nonfallers.<sup>48,49</sup> Fallers demonstrate increased stride frequency, decreased stride length, reduced ankle plantarflexion and hip extension, and a greater minimum toe clearance. These adaptations are likely demonstrated by fallers in an attempt to reduce gait pattern variability and maximize stability.<sup>48</sup> Without subject fall history we are unable to speculate the potential this may have had on trip biomechanics.

In the future, interventions aimed at improving overall paretic limb flexion during late stance/early swing by targeting multiple joints may be more effective at preventing trips than those targeting flexion of a single joint. The pre-swing phase of the gait cycle during which we observed significant alterations, suggests that gait rehabilitation efforts should focus on increasing paretic limb muscle strength and joint coordination during this period to increase the success of limb progression during swing. Implementing therapies that address the underlying kinematic and kinetic abnormalities leading to trips may assist in preventing falls and falls-related injuries in individuals with chronic stroke. Assessment of these trip-related biomechanics

in individuals with a history of falls may be useful for falls prediction or identification of falls risk in the post-stroke population.

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